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Trends in Earth Monitoring and Observation Satellites
– Advances in Monitoring and Observation with Satellites in File-formation Flight –

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1 Introduction

Earth monitoring and observation utilizing satellites is characterized by the ability to grasp broad global conditions quickly and without interference from weather or national borders.

The diverse purposes of work performed by Japanese satellites include space-related development of various satellite technologies, such as communications satellites that upgrade social infrastructure, weather satellites that serve the people, resource satellites that investigate resources, information and monitoring/observation satellites that ensure national security, and satellites for space exploration and other scientific research.

Among those working with satellites, there is awareness that the satellites that protect Japan must not only observe Japan and, obviously, issues such as global warming, water resources and food issues, but also monitor the East Asia region, including geopolitical issues, and indeed the entire world. Under these circumstances, earth monitoring and observation satellites not only have scientific goals, they are increasingly important in protecting the nation and obtaining information needed to set policy.

2 Satellite file-formation flights

To carry out earth monitoring and observation with satellites, conventionally a large satellite bus[*1] is loaded with numerous observation sensors. For example, Japan's ADEOS-II (launched December 14, 2002) weighs 3.7 tons and carries 5 kinds of sensors, and the European Space Agency's (ESA) ENVISAT environmental observation satellite (launched February 28, 2002) weighs in at 8.2 tons with 10 types of sensors.

As an alternative to these massive satellites with numerous sensors, NASA and others propose lining up small satellites with relatively few sensors (1 or a few) and flying them in formation. Unlike aircraft that fly in parallel formations, the nature of satellite orbits requires that satellite formations consist of multiple satellites flying consecutively in the same orbit, orbiting the earth much the way a train travels over the ground. From the perspective of the ground under that orbit, satellites pass overhead in succession at intervals of tens of seconds to over ten minutes.

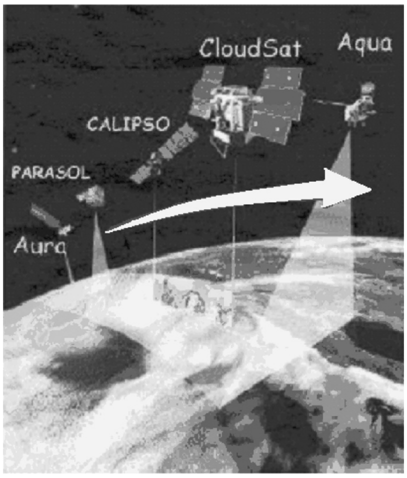
In the past, positioning control over such formation flights was by no means easy. The loading of GPS receivers on satellites, however, has enabled the necessary degree of precise control over position and timing required for formation flying. These file-formation flights are expected to lead to new developments in satellite observation.

For example, NASA has a project[1] called "Taking the A-Train"[*2] in which a formation of satellites is led by Aqua and ended by Aura (see Figure 1). Before the A-Train, satellites have already been launched in the same orbit as existing satellites, resulting in formation flying. For example, Landsat-7 is now followed in the same orbit by EO-1, SAC-C, and Terra[*3] at about 30-minute intervals. (The time varies with orbital corrections.)

Table 1:Overview of the A-Train

Satellite name	Launch date (scheduled launch date)	Developing organization, purpose, etc.	Sensors
Aqua	May 4, 2002	Earth Observing System (EOS) series satellite, collects data on global water cycle	Advanced Infra-Red Sounder (AIRS), Advanced Microwave Sounding Unit (AMSU-A), Humidity Sounder for Brazil (HSB), Advanced Microwave Scanning Radiometer for EOS (AMSR-E), Moderate-resolution Imaging Spectroradiometer (MODIS), Clouds and the Earth's Radiant Energy System (CERES)
CloudSat	Autumn 2004	NASA satellite	CPR (Cloud Profiling Radar)
CALIPSO	2004	NASA satellite, observation of atmospheric clouds and aerosols	Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), Imaging Infrared Radiometer (IIR)
Parasol	Following the others	An approximately 100-kg microsatellite to be launched by CNES	Polarization and Directionality of the Earth's Reflectance (POLDER)
Aura	January 2004	NASA, EOS series observation satellite, to collect data on ozone and changes in air quality	High Resolution Dynamics Limb Sounder (HIRDLS), Microwave Limb Sounder (MLS), Ozone Monitoring Instrument (OMI), Tropospheric Emission Spectrometer (TES)

Figure 1:The CloudSat Mission and the A-Train



Source: CloudSat satellite team document describing the sensors

3 The relationship of monitoring and observation sensors and satellite buses

3.1 The advantages and disadvantages of large satellite buses and multiple satellite buses

The proverb "Don't put all your eggs in one basket" is sometimes brought out, with sensors as the eggs, when discussing the risks of loading multiple sensors onto large satellites. That is because the risk of launch failure for satellites is still extremely high. For example, even the Space Shuttle, a manned system with a high design safety factor, is designed to have a success rate of 99.5 percent. (With 2 accidents in 109 launches, its actual success rate is 98 percent).

That is why even today any enterprises utilizing satellites for earth monitoring or observation must consider risk. However, sensors do the bulk of the work in satellite monitoring and observation, with satellite buses as nothing more than the necessary platforms that support them. That raises the question of how sensors should be loaded on satellites. For example, the first question whose pros and cons must be examined is whether to place multiple sensors on a single satellite or to launch them separately. Suppose that three sensors are to be launched, and the success rate is k = 0.9. If the three sensors are loaded on a single satellite bus, the probability that none will make it to orbit is 0.1. If, on the other hand, the sensors are loaded on three separate satellite buses, the probability that none of them will make it to orbit is only 0.001. Utilizing multiple buses greatly raises the probability that some sensors will be successfully launched. If, however, we look at the probability that all three sensors will exist in orbit simultaneously, the probability for a single satellite bus is 0.9, while for three satellite buses it is only 0.729. In that case, the single satellite bus has the advantage.

In addition, the operation of each of the three sensors in space can be assigned a result (value) of p and the expected value can be considered (This does not consider the cost of the rocket used for launch). In the case of both a single satellite bus and three satellite buses, the expected value is 3kp. In other words, from the perspective of launch risk alone, there is no essential difference in the expected value of sensor operation between a single bus and multiple buses. From the perspective of the expected value of the sensors' results, there is no advantage in lowering the risk with multiple satellite buses.

When the value of each sensor is increased through their working together to collect data, however, a higher value is achieved by launching them on a single satellite. Continuing with the same example, if the three sensors must all be present to obtain useful data, then launching a single satellite is clearly advantageous.

3.2 Policy advantages of multiple satellite buses

On the other hand, in the event that technological advances decrease the costs of launch rockets and satellite buses so that the overall costs of multiple satellite launches to single-bus systems and multiple launches become more realistic, multiple launches offer several advantages from a satellite-related policy perspective. The following are some examples.

(1) Avoidance of interruptions of observation

In general, continuous long-term earth monitoring and observation utilizing satellites brings additional value to the data obtained because changes in the earth's surface and so on can be detected. Therefore when, for example, a launch fails or a satellite malfunctions and no observation sensor exists-in other words, when there is an interruption in earth monitoring and observation-it has a negative impact on the execution of policy. A multiple bus system can avoid such interruptions.

(2) Spreading costs over time

Combining a large satellite with multiple sensors requires the concentrated investment of funds during a limited period. The nature of earth monitoring and observation, however, requires that they be continued over long periods. Preparing multiple small satellites could spread budgets over longer periods, making it easier for policies to be implemented.

(3) Enabling easier participation in satellite observation ventures

For example, if an institution (e.g., private sector or academic) develops a unique sensor and that sensor requires the supplemental use of data from other sensors, the institution can participate in a formation of satellites that provides all the necessary sensors without having to prepare them all on its own satellite. The result is that its observations can be made at a lower cost.

(4) Standardization through the manufacture of multiple satellite buses

Manufacturing multiple, small satellite buses and their rockets will lead to standardization of manufacturing processes and products. That can be expected to lead to various kinds of profits for manufacturers as well as reduced procurement costs. Furthermore, increasing the reliability of rockets manufactured in large numbers for the launch of small satellite buses is probably more possible than increasing the reliability of only a few rockets manufactured to launch large ones.

4 Characteristics of satellites flying in file formation

4.1 Classification of satellite formations

Formations are classified by purpose as follows.

(1) Formations that strictly maintain relative positions in orbit

Primarily these use multiple satellites to function as interferometers studying deep space. However, examples of those that engage in earth monitoring and observation include the U.S. military's TechSat 21 project (high-resolution military radar) and the ESA's Cluster II (four satellites performing high-precision observation of earth's electromagnetic field)[2]. Both are examples of projects planned from the beginning as formation flights for specific purposes.

(2) Formations that more loosely control relative positions in orbit

In contrast, formations that offer more flexible earth monitoring and observation and the possibility of lower costs are likely to be important in earth monitoring and observation from now on. The formations headed by Landsat-7 and Aqua mentioned above are two such observation projects.

Formations that maintain or measure strict positioning comprise satellites that have all been designed and planned for specific purposes. Such plans do not change for the life of the project. In the sense that their operation is fixed, they do not differ essentially from conventional large satellites.

Formations that more loosely control their positions in orbit, however, comprise satellites that join in the same orbit despite having completely different purposes. This opens the possibility that new scientific or policy value may be created, or that the reason for the satellites' existence may be transformed as more of them join even though that was not part of their original purposes. This would lead to satellite observation that is without precedent.

Because multiple satellites must simultaneously operate in such formations, complex satellite operation and precise orbital insertion are required. Their greatest advantage, however, is that comprehensively processing the data from each sensor enables high-quality data to be obtained.

As mentioned above, the mutual distance maintained in formation flights normally would vary from tens of seconds to over ten minutes. Earth conditions will not change greatly during such intervals. Therefore even if a group of sensors are not loaded on the same satellite bus, the same point on earth or the same region can be monitored or observed with different sensors or with identical sensors utilizing different methods. In other words, measuring earth conditions from a variety of aspects enables valuable data to be collected.

4.2 The advantages of formation flying from a sensor perspective

From the perspective of earth monitoring and observation, multiple sensors on multiple satellites flying in formation result in the creation of a virtual giant satellite that can be simultaneously operated. A number of advantages of formation flying over single large satellites can be noted.

(1) Operation of sensor clusters

For example, earth observation satellites have become large in response to various scientific requirements. As mentioned above, the ESA's Envisat large earth observation satellite launched in March 2002 carries 10 different kinds of sensors. In such cases, operation of multiple sensors is extremely complex. For example, because all the sensors share the same power source and data transmission system and are controlled on the same satellite body, resources related to operation must constantly be adjusted among the sensors. Because satellites flying in formation are independent, very large numbers of sensors can be operated together in a way that is not possible with conventional earth observation satellites.

(2) Avoidance of inter-sensor interference

For example, when active sensors for cloud radar and measurement of electric wave dispersion are loaded on the same satellite, it must be carefully designed so that the electric waves put out do not cause interference with other sensors. Furthermore, sensors with mechanical vibrations or moving parts often influence other sensors, so the same careful design of the sensors and the satellite bus is required. Because the individual satellites in a formation flight can be freely equipped, the problem of inter-sensor interference is greatly abated.

(3) Forming sensors to detect phenomena that change over short periods

Although we stated above that earth conditions do not change greatly over short periods, satellites in file formation can detect phenomena that do change over very short periods. They can detect the speed of changes in rapidly changing phenomena on the earth's surface. For example, they can detect flood conditions and changes in natural formations caused by natural disasters. From the current formation of Landsat-7, EO-1, SAC-C, and Terra, Tanaka, et al.[3], use image data from Landsat-7 and SAC-C (passing over the same surface points about 28 minutes apart) to estimate the speed and distribution of currents in the Strait of Magellan and from Landsat-7 and EO-1 (images obtained 54.5 seconds apart) to estimate the course of ships in Yokohama Harbor.

5 The influence of satellites in formation on earth monitoring and observation activities

When satellites build formations, points differing from the planning, operation, and data of conventional earth monitoring and observation satellites will appear. This will likely have great influence on overall policy related to earth monitoring and observation. The following are some areas where this may be expected to occur.

(1) Increased flexibility in planning for sensor development and operation

Sensors that observe topical earth sciences phenomena must be able to undertake measurement in a timely way. Basic sensor types are expected to obtain observed values necessary for weather forecasting models, and at the same time function as sensors to obtain basic data that illuminate topical phenomena. Because satellites in file formation make possible the combination of standardized satellite buses and unique sensors, individual sensors can be developed and planned in a flexible manner. For example, basic sensors can be designed for maximum stability of operation, while sensors for topical uses can be developed quickly. Because the development and operation of large satellites with many sensors generally required planning and operational adjustment among the sensors, long term planning and development and high overhead costs were often required.

(2) Gradual increase in monitoring and observation data from satellites in formation

In many cases, data obtained from an individual sensor can be combined with data from others sensors to increase the value of that data. Furthermore, combining data from different types of sensors opens the possibility of new scientific and policy knowledge. Current single earth monitoring and observation satellites cannot change their sensors for the life of the satellite, so new technologies and ideas cannot be implemented until the next satellite is ready.

In contrast, after a formation of satellites has temporarily formed, the data from those satellites' sensors can be utilized in planning for the development and operation of a new sensor to be added to the formation. The result is that new technologies and ideas can be implemented faster than with single satellites. When the number of sensors in a satellite formation is increased in this way, the value of the monitoring and observation that utilizes them is increased along with the number of sensors participating in the formation.

(3) Concentration of the operation of satellites in formation and data collection and distribution

Even though control of the individual satellites comprising a group of satellites in formation is relatively easy, and even though they may be owned or have been launched by different institutions, from a cost perspective it is desirable that they be operated by a specialized institution such as JAXA. Because of convenience to users and cost considerations, the operation of the accompanying sensors, in other words, the receipt and distribution of earth monitoring and observation data, will likely be handled by the same institution that operates the group of satellites.

6 Conclusion

Japan has outstanding earth observation sensors such as the Global Imager (GLI), the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), and the Precipitation Radar (PR), and its sensor development capacity is not inferior to that of countries such as the United States. For example, GLI obtains images of ocean and land surfaces on a very broad range of wavelengths, leading to new scientific developments relating to those areas. The AMSR-E measures faint microwaves radiating from the earth's surface and the atmosphere to estimate water vapor volumes and soil moisture. Its antenna aperture is in the largest class of any scanning radiometer. The sensor is loaded on the ADEOS-II and on the United States' Aqua satellite. PR is the world's first satellite=loaded precipitation radar. It is the first satellite sensor to capture a broad range of three-dimensional data on the mechanisms of precipitation, and provides information important to research on the global water cycle. PR is the main sensor on the satellite bus of the United States' TRMM, and a new version is now being planned.

These sensors are loaded on several satellites along with other sensors, and are playing an important role. This demonstrates that Japanese sensors are key instruments that obtain data that increase the value of other sensors. Japan has led the world in sensor development. It must be noted, however, that Japanese efforts to form a monitoring and observation system that continually prepares and develops those sensors, involves domestic and overseas users, and responds to diverse user needs have been insufficient.

As we mentioned above, to realize groups of satellites in formation, more than the technical development of satellites and sensors is required. Cooperation with other countries and advances in the management of earth monitoring and observation that seek to add overall value are also needed. With its outstanding key sensors, Japan's planning and operation of its own groups of satellites in formation would respond to social needs, particularly those for safety and peace of mind. From the perspective of space policy development as well, it should be engaged in for the sake of the development of space transport systems and satellites.

Glossary

*1 Satellite bus

The basic system of a satellite, which does not include the various sensors loaded on the satellite.

*2 Taking the A-Train

A play on Billy Strayhorn's composition "Take the 'A' Train," best known as Duke Ellington's signature song.

*3 Landsat-7, Terra, EO-1, SAC-C

Landsat-7 was launched on April 15, 1999, Terra on December 18, 1999, and EO-1 and SAC-C were launched together on November 21, 2000.

Reference

[1] "Changes in Polar Ice Concentrations," April 22, 2002.: http://www.gsfc.nasa.gov/topstory/20020418aqua4.html

[2] "Survey examination of guidance control technology for formation flight satellites", National Space Development Agency of Japan (NASDA).: http://giken.tksc.nasda.go.jp/seika/gaiyou/H11/34files/

[3] Sotaro Tanaka, Kenji Takasaki, and Jose Kuba. "Remote sensing by tandem operation," RESTEC, 51, June 2003. (in Japanese)

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